FAST SWITCHING AND PRECISION RELATIVE ASTROMETRY AT THE DSN

Walid Majid

&

Durgadas Bagri

Jet Propulsion Laboratory

California Institute of Technology, Pasadena, CA, USA.

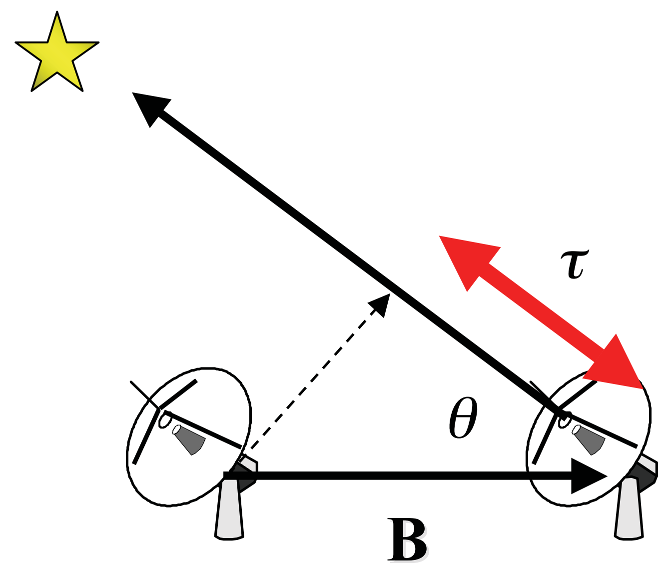
Outline

- Radio Interferometry Basics
- Measurements of Spacecraft Angular Position
- Reducing Calibration Errors
- DSN Observations & Data Analysis
- Calibrator Density Determines Robustness
- Conclusions

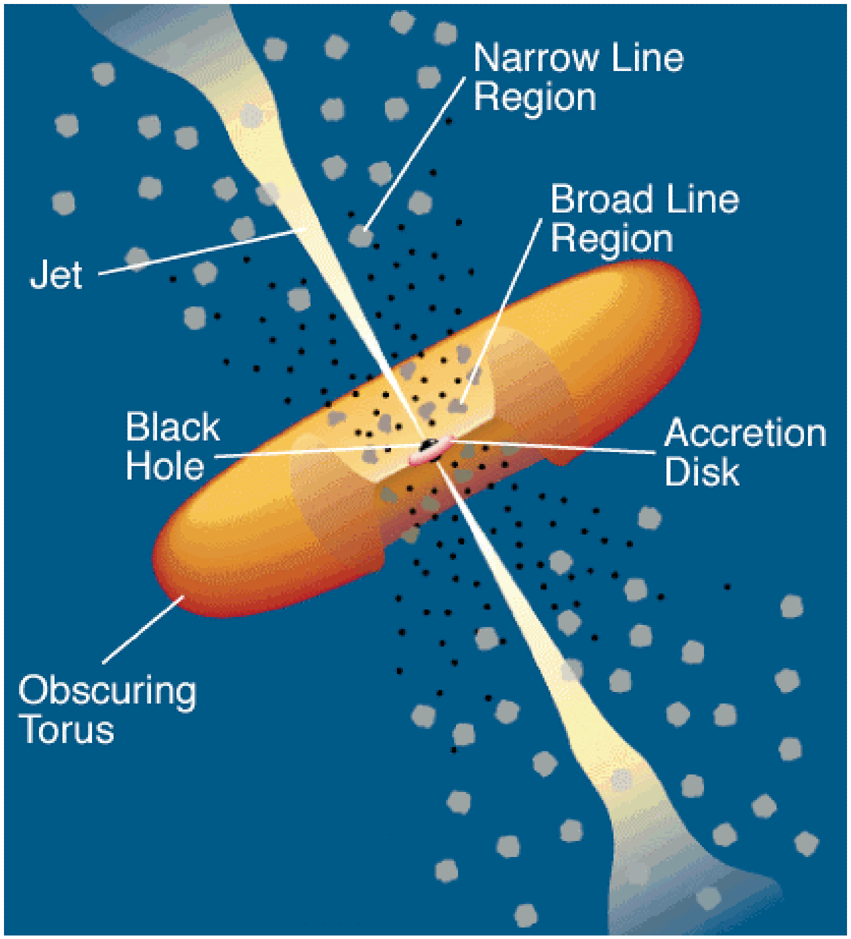
Radio Interferometry Basics

- Geometric delay given by $\tau = B\cos(\theta)/c$
- Angular measurement error improves with smaller delay error and longer baseline $\sigma(\theta) \propto \sigma(\tau)/B$
- Interferometer measures $\phi(t,\nu) = 2\pi\nu\Delta\tau(t)$
- Use of phase delay solution improves thermal noise error
  - Phase versus group delay
  - Phase delay provides far better precision (x50 @X-band), however cycle ambiguity to be resolved

$$\tau_\phi \propto \frac{\phi(t)}{\nu} + \frac{n}{\nu} \qquad \tau_g \propto \frac{\Delta\phi}{\Delta\nu} \qquad \frac{\sigma_{\tau_\phi}}{\sigma_{\tau_g}} = \frac{\Delta\nu_{rms}}{\nu}$$



Active Galactic Nuclei



(Credit: C.M. Urry and P. Padovani)

Redshift z~ 0.1 to 5

Distance: billions light years

Parallax = 0

Proper motion **< 0.1 nrad/yr**

Very weak sources

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

$$\Delta S = \frac{T_{sys}}{G\sqrt{n_p \Delta\nu\,\tau}}$$

need large antennae

34 - 70m

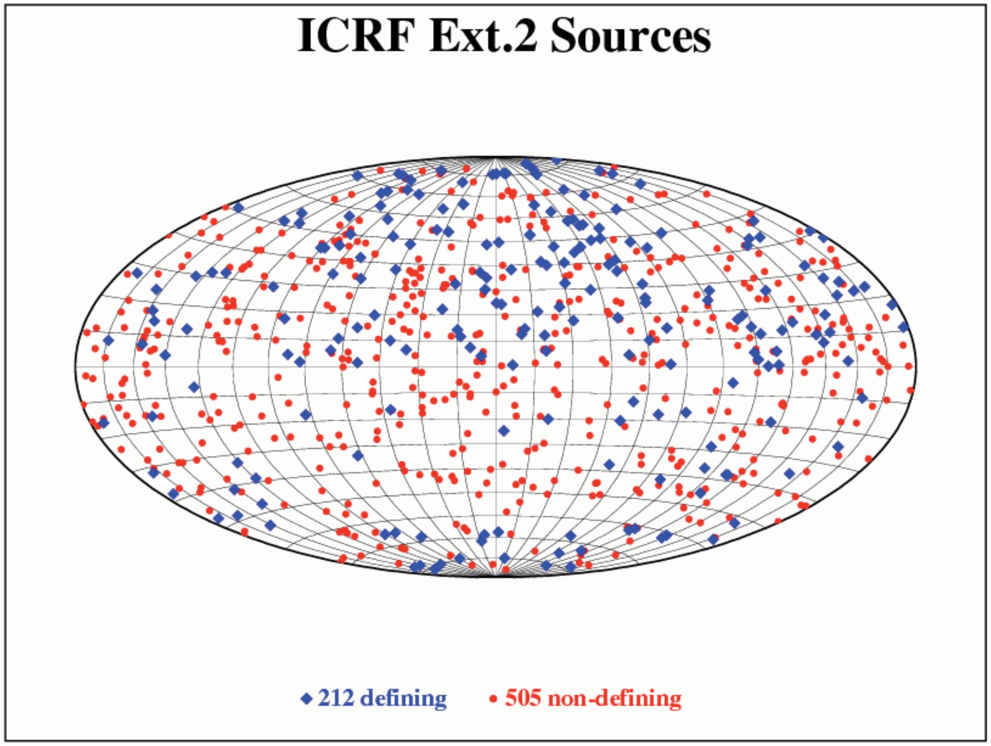
lots of Hz bandwidth

100 Mbps – 1Gbps

low system temp

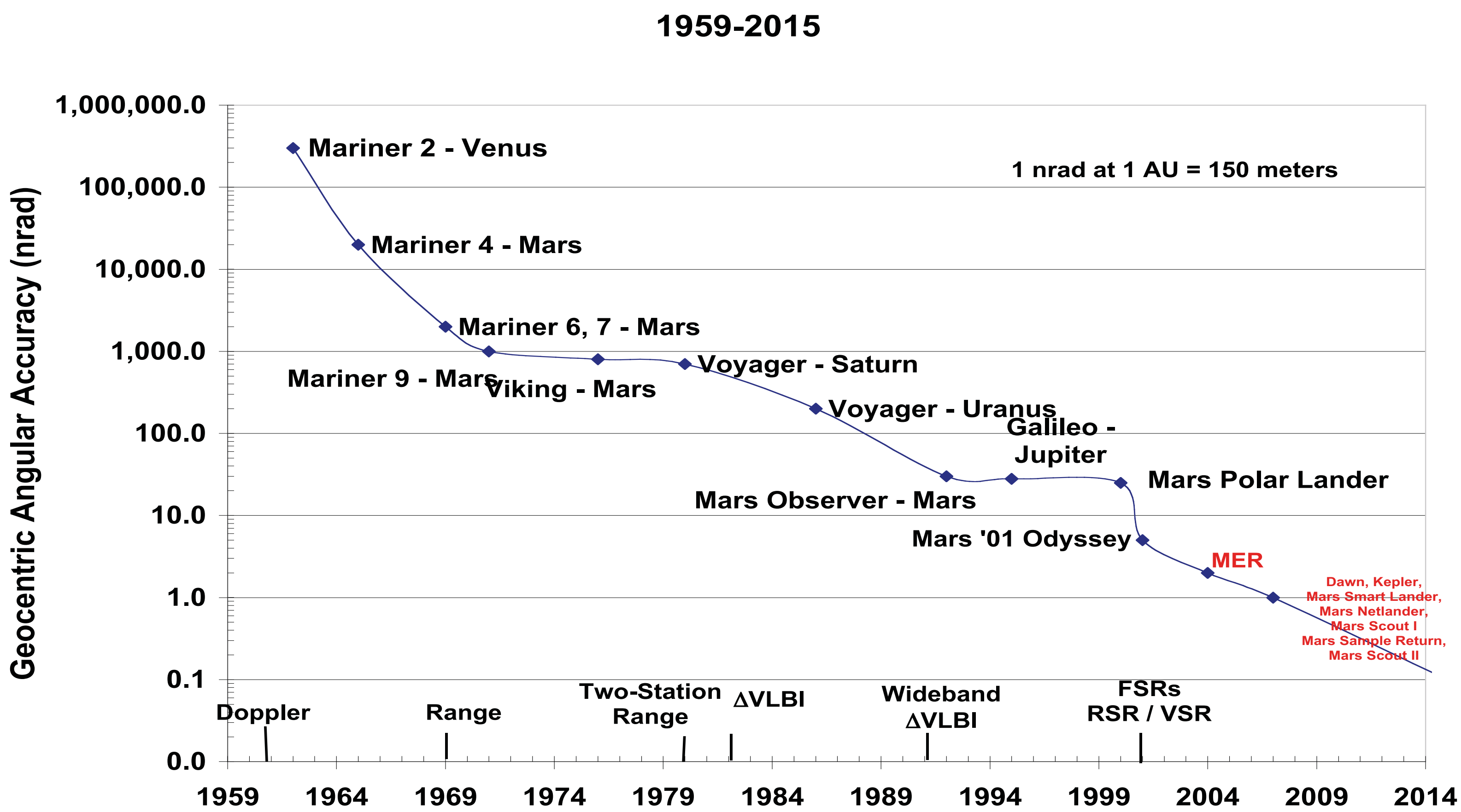
Tsys = 20-40 Kelvin

International Celestial Reference Frame (ICRF)



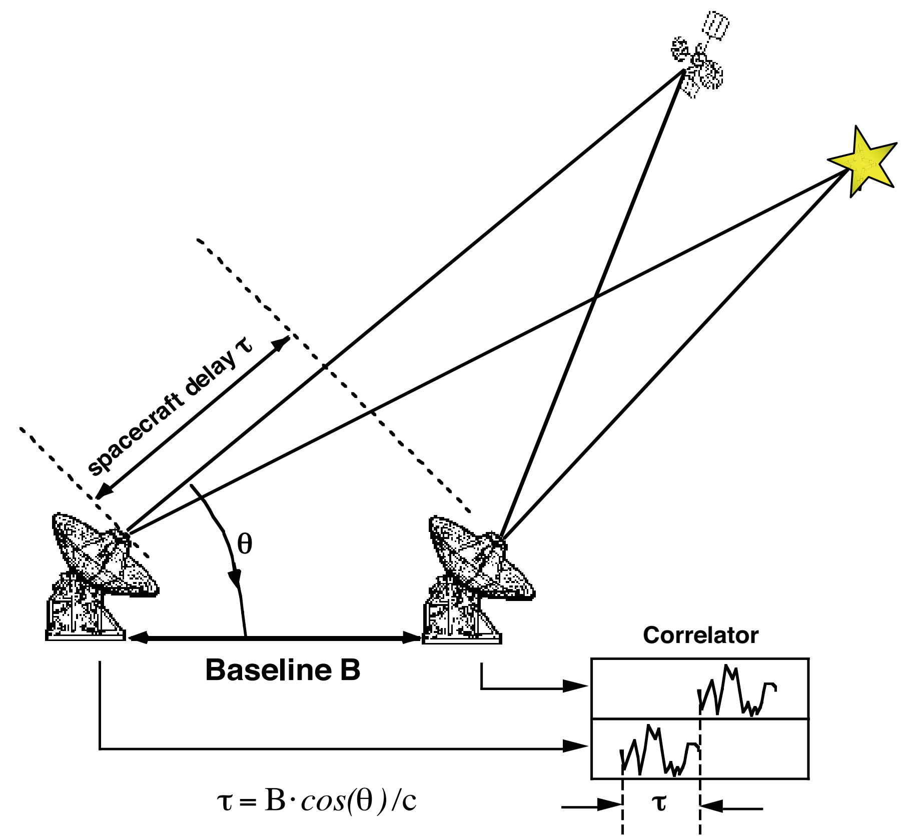
- S/X data and analysis through 1995
- ICRF-Ext.1, ICRF-Ext.2
- 212 defining sources
- Position uncertainty ≥ 250 μas
- Accuracy of axes ~30 μas
- Orientation independent of equator, ecliptic and equinox
- Fey et al. 2004

Steady Improvement of Accuracy in Angular Position Measurement



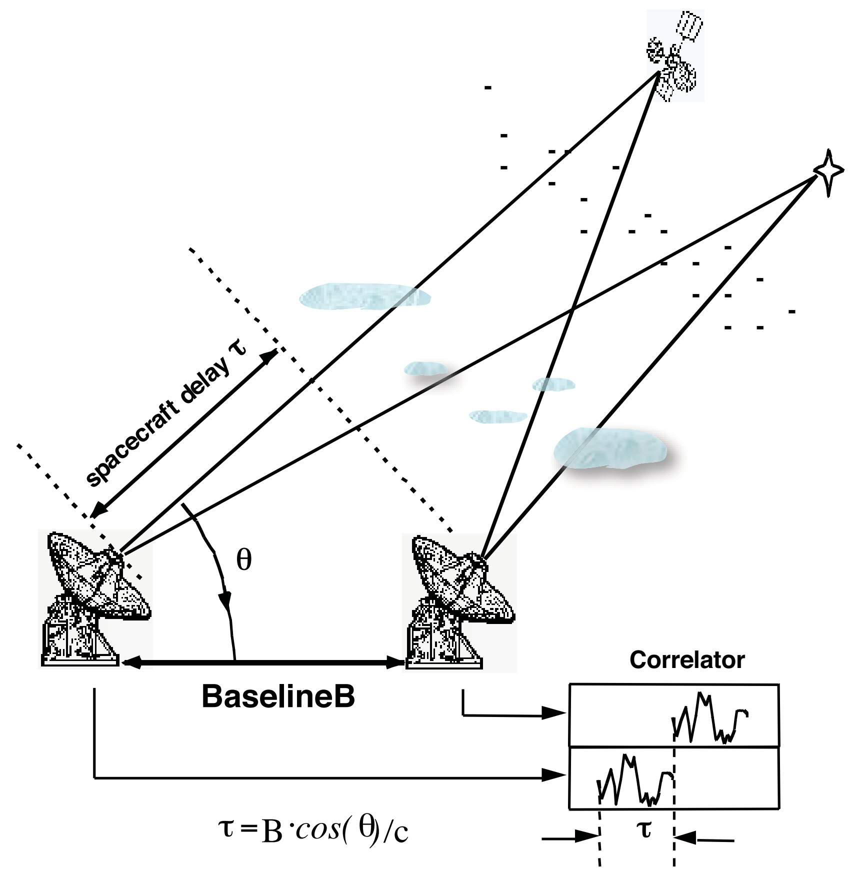
Spacecraft Angular Position

- Measurements made using reference calibrator
- Using spacecraft tone signal
- Intercontinental baselines ~8000 km
- Group delay measurement - VLBI
- Calibrator few hundred mJy with 5-10 degrees angular separation
  - 10-15 minute integration time
- Bandwidth few hundred MHz at X-band (8.4 GHz)
- Measurement accuracy 2-5 nanoradian (< 1 mas)



Improved Differential VLBI Techniques

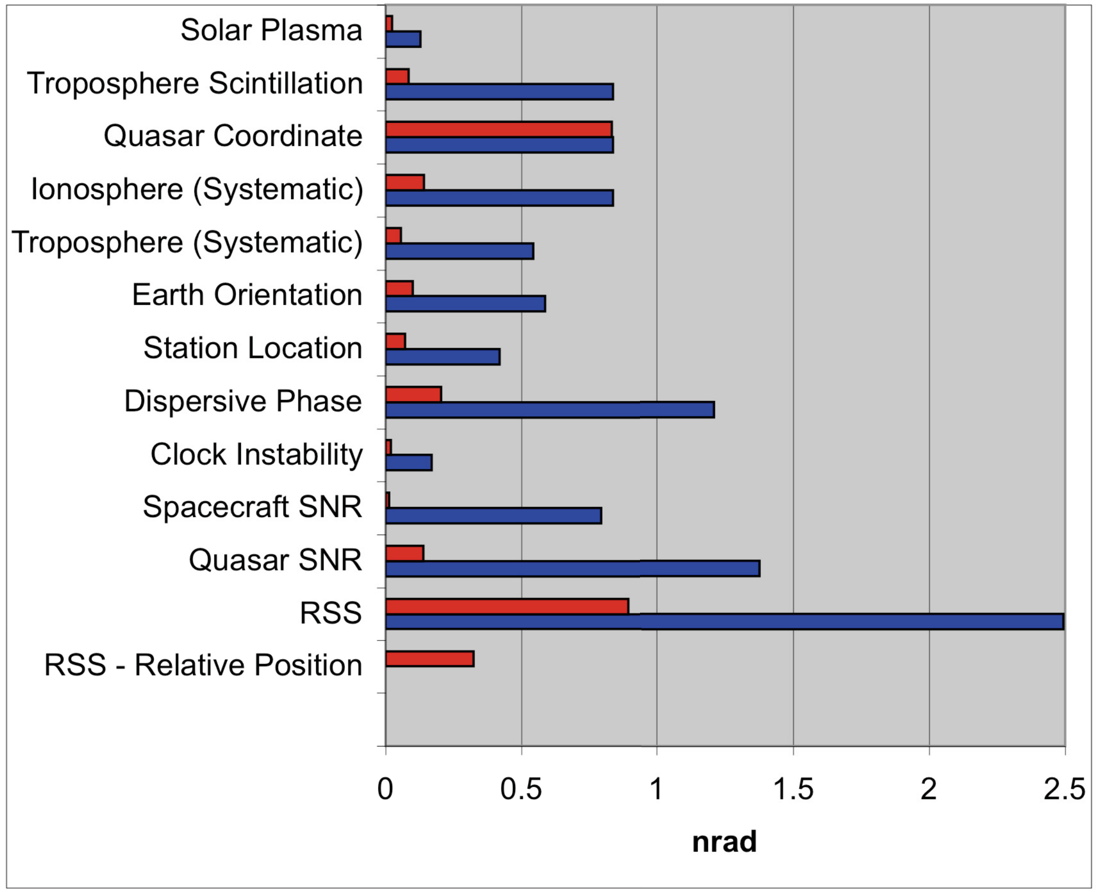
- Improve accuracy by minimizing calibration errors
- Reduce BOTH temporal and angular separation between calibrator and target by fast switching between nearby (small angular separation) calibrator and target
  - Angular dependent model errors (e.g. due to media) are decreased ~ linearly by angular separation, e.g., 1° separation ==> 5X decrease in error
  - Temporal model delay errors are removed to first order
  - Unmodeled delay scatter due to media between sources ~ few psec for source separation of 1° and cycle time of 1 minute



Improved Techniques (cont.)

Error budget estimate @ X-band

- Smaller switching angle decreases errors due to
  - Media, Geometry
- Faster switching time decreases errors due to
  - Media, Bandpass errors
- Use of phase delay decreases thermal errors
- Bandpass calibration reduces dispersive phase errors
- For absolute measurement Quasar catalog error dominates

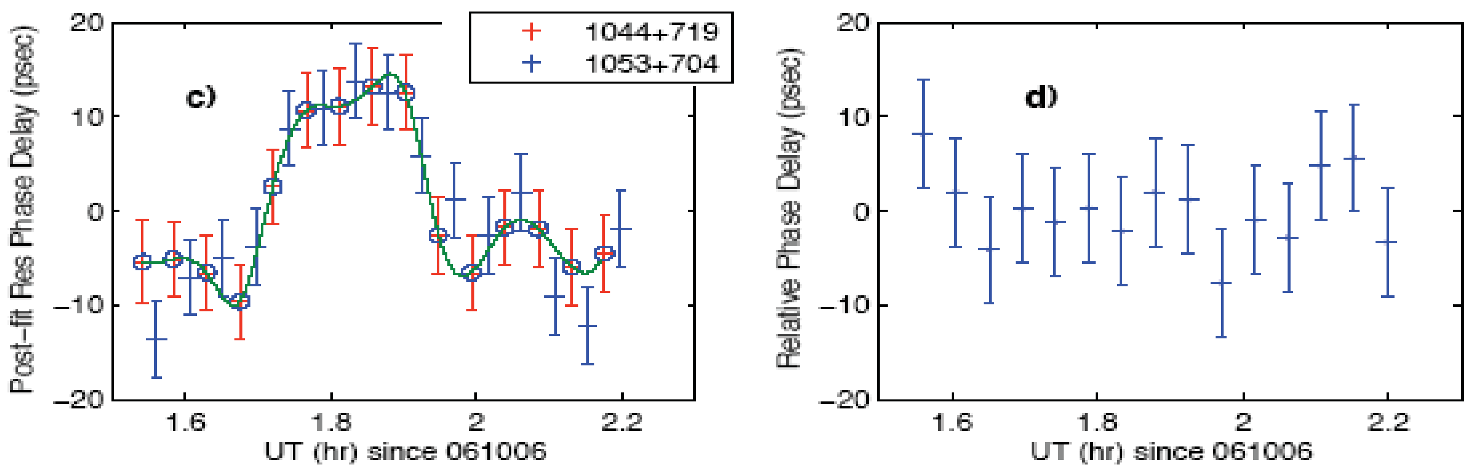


DSN Observation of Quasar Pairs

- Five pairs of quasars ~1-2^{o} angular separation.
- Cycle time 1 minute; Two epochs.
- Pair of 34m antennas on Goldstone-Madrid baseline
- Obtain ~5 psec relative rms error, corresponding to ~<0.2 nrad (Majid & Bagri JPL IPN report, Feb 2008)

Table 3: R esults of difference observables after least square analysis described in text.

Target Name	Calibrator Name	Angular Distance (degrees)	Phase Resid (psec)	Angular precision (nrad)
0153+744	0159+723	2.2	6	0.25
0814+425	0805+410	2.3	3	0.14
1020+400	1030+415	2.4	6	0.25
1053+704	10444+719	1.7	3	0.14
1842+681	1849+670	1.2	4	0.17



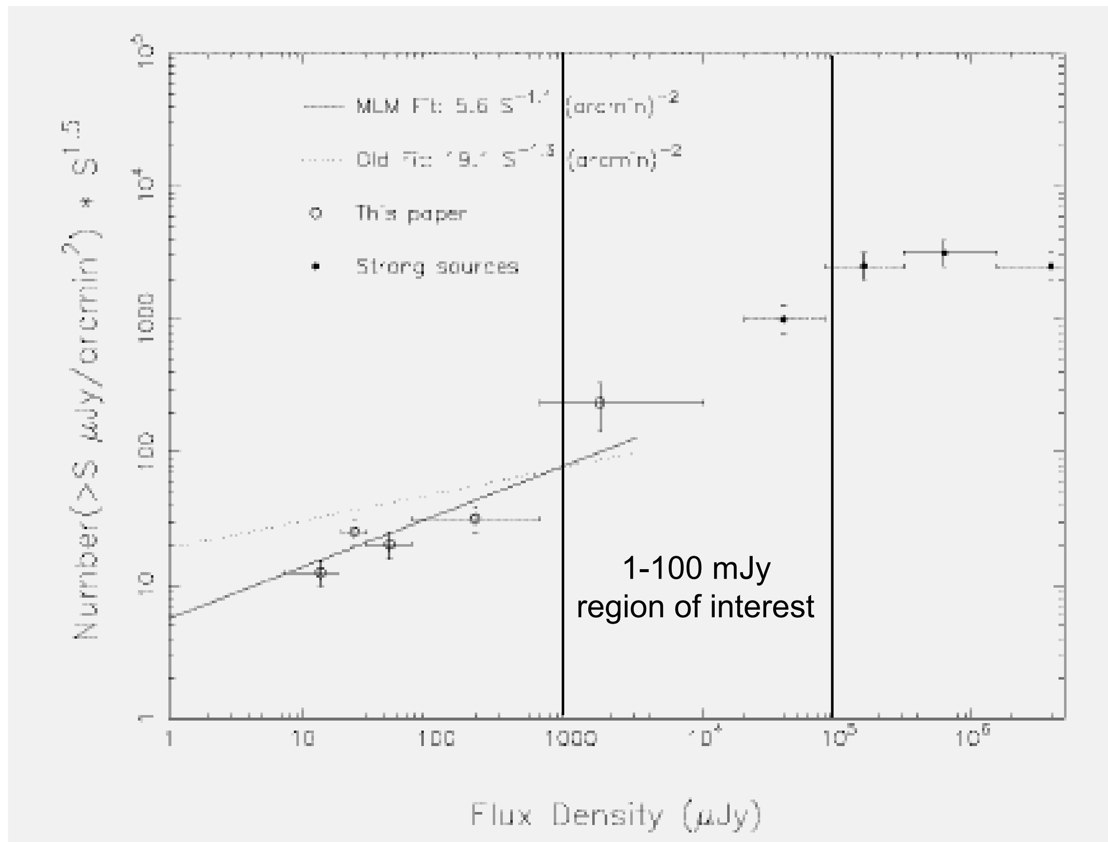
One cycle at X-band is 120 psec

Relative Astrometry (cont)

- Expect delay errors to decrease by reducing switching time and angle between observations of calibrator and target; use of phase delay improves thermal noise error; calibrate bandpass to improve dispersive phase errors
- Initial set of observations at DSN show promise
- Further observations with faint pairs of quasars will be carried out
- Demonstrate capability with observations of spacecraft with faint nearby calibrator
- May be able to use 50 mJy calibrators ==> 1^{o} mean distance
- Our ability to take advantage of such techniques at the DSN depends on: How often can we find a calibrator with flux density > 50 mJy within 1^{o} of spacecraft?
- Source structure causes problems at ~< 0.5 nrad level accuracy
  - Recent observation of calibrator is required prior to spacecraft angular position measurement
  - However, weak sources tend to be more compact (less structure)

What Fraction of Radio Sources are Compact?

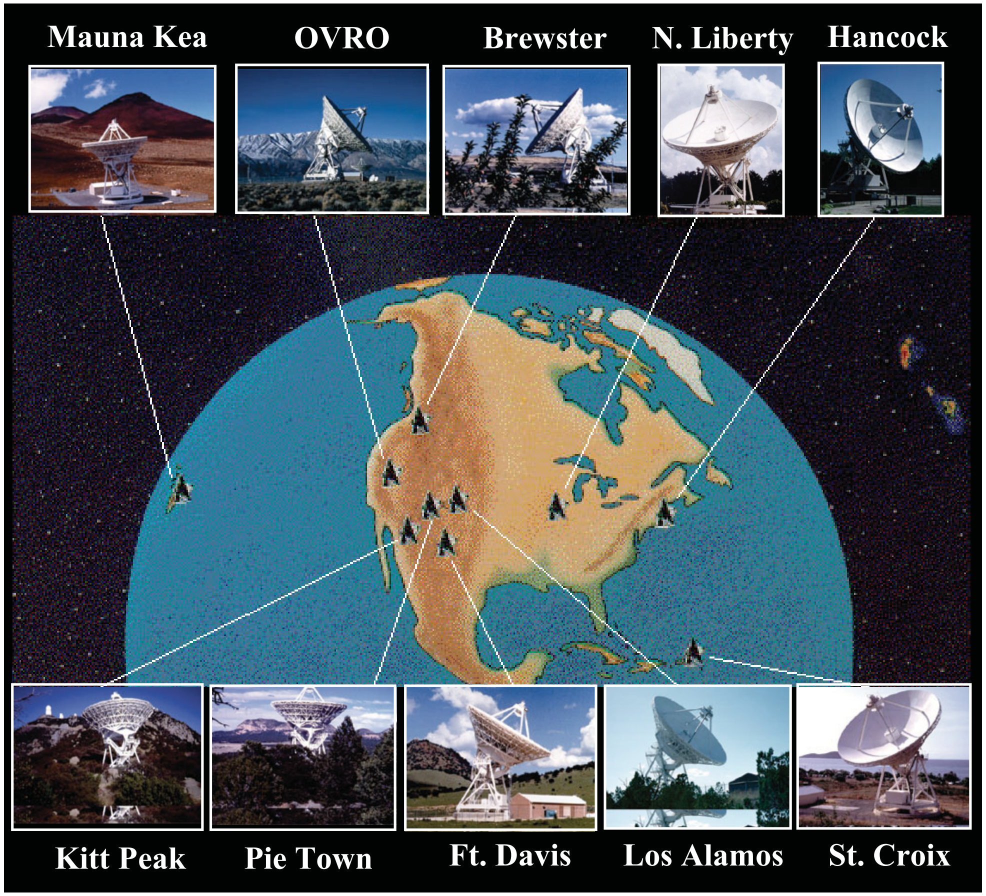
- Radio source count density exhibit pronounced deviation from flat Euclidean space with uniform source distribution
- Radio source count measured at various frequency bands
  - down to micro-Jansky level @ X-band
- Using spectral index distribution estimate density @ Ka-band (Majid & Bagri 2006)
- **Not all radio sources useful as VLBI calibrator**
- Determine fraction of sources that are compact
- Improve radio source count estimates in 1-50 mJy region



Fomalont et al. 2002

Compactness Fraction (cont.)

- Nature of high frequency samples not well known
- Estimates of compactness fraction of faint sources at high frequency 10%-80%
- Have started a program at the VLBA to determine what fraction of radio sources are compact at the mas level
- VLBA observation of sample > 10 mJy carried out (Majid, Fomalont, & Bagri in preparation)
- Preliminary results ==> 30% of sources have compact cores
- Sample of 1-10 mJy to be observed at VLA+VLBA - proposal successful
- For sample < 1 mJy also need GBT + DSN 70m antennas



Summary: What may be Achievable at the DSN

- We are developing new techniques to improve astrometric accuracy
  - Reducing switching time (~60s) and angular separation (~1^o) between quasars
  - Use of phase delay & bandpass calibration
  - Techniques also applicable with future DSN Array
- Initial set of observations carried out at the DSN show great promise
- Continue DSN observations using fainter calibrators to study robustness and to verify and validate error estimates
  - Eventually demo technique with spacecraft measurements
- Viability of technique depends on existence of sufficient number of calibrators
  - Determining what fraction of radio sources are compact at the VLBA
- May be able to use calibrators with flux density ~ 50 mJy with calibrator <distance> 1^o
- Relative precision of ~0.5 nrad may be achievable
- Absolute measurement always depends on knowledge of calibrator position
  - Catalog maintained and improved

FINITO

DSN Observations (cont.)